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Location of transformers during the extension of an electricity distribution network☆

Onur Akar[a], Umit Kemalettin Terzi[b], Okan Ozgonenel[c,*]

[a] Department of Electronic and Automation, Marmara University, Istanbul, Turkey
[b] Department of Electrical-Electronic Engineering, Marmara University, Istanbul, Turkey
[c] Department of Electrical-Electronic Engineering, Ondokuz Mayis University, Samsun, Turkey

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ABSTRACT

The electricity network of a country is in continuous development, including the distribution transformers that provide power within a city. Efficient electricity networks depend on the good implementation of the principles of network planning and development. Moreover, technology development and the increasing standard of living are creating greater electricity demand. Besides, housing developments alter the need for electricity in an urban area and will require changes to control load density, adjustment of the voltage on distribution lines, installation of new lines and substations, and restructuring of existing ones. This study develops new mathematical and geometric methods that can be applied to all Low Voltage distribution networks to investigate load distribution, the effects of change and, provide a tool for distribution network planning. The analysis included the electrical power values to the new transformer, the shortest distribution routes between the transformers, and the costs, and provided optimum locations for new transformers. In this way, distribution network planning has been approached with a new method.

1. Introduction

In general, the electricity industry focuses on energy needs and its production, while the distribution of the produced energy receives less attention. With the development of technology and an increasing standard of living, electricity demand is increasing, and the construction of new housing developments causes changes to the electricity density in urban areas. As electricity use increases, a country's electricity distribution networks must constantly evolve to maintain a city's electricity supply. The formation of an efficient electricity network can be achieved by the good implementation of the principles of network planning and development. This can be accomplished by controlling the change in load density, installing new transformer stations and lines adjusting the voltage in the distribution lines, or restructuring existing ones.

However, increasing the voltage in lines in a city, and establishing new substations that will connect to the grid is a complex process. Moreover, the rapid changes that can take place within a city centre make it difficult to determine where to locate new cables and new substations. However, if general building principles and grid planning are established, this will allow future expansion without significant changes to the network [1–3]. In a technically and economically planned network, it is important to select the optimum parameters for the network in the first stages of design, evaluate the forward loads objectively, activate new capacity, provide spare capacity for new lines, and determine the location of possible substations. Besides, planning should consider the structure and arrangement of circuit breakers, disconnectors, protection elements, and cabling. Moreover, good grid planning should reduce operating costs.

Distribution Modern grid planning will include intelligent substations and smart grids that can communicate. These can provide information on the cause of failures and reveal the impact onconsumers. In addition, such information can assist in planning for additional network load and new consumers to be connected to the electricity network [4–6]. Distribution systems are complex and large. Reactive currents increase the rating of the distribution components and cause losses. The lost power in distribution systems is about 13% of the total power produced. Although increasing automation of distribution systems has reduced this figure, optimizing the restructuring of the distribution system is important to reduce losses further. Where no existing infrastructure exists, the distribution network must be expanded in line with

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* Corresponding author.
E-mail address: okanoz@omu.edu.tr (O. Ozgonenel).

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the projected demand and in a way that will balance the capacity of the system. In recent years, there has been a shift to electricity being generated by renewable energy sources, which can have a significant effect on the performance of distribution systems. In line with the developments in energy generation systems, new planning strategies have been proposed for energy distribution systems. To plan a good electricity distribution network, it is necessary to know where energy enters and leaves the transmission system, where energy is used or lost in the distribution system, and where the energy losses are the highest [7–9]. Moreover, Good planning should identify the power and location of the distribution transformers to reduce those losses. According to the power of the transformer, the number of transformers in the feeder to which it is connected, load density, and the service area formed within the network according to the load factor can be called transformer Coverage-Area (CA). As an approximation, it can be considered as the area that a transformer feeds or serves in square kilometers (km^2). To determine the optimum location of power distribution substations, their CA and power value, studies have been conducted, and algorithms have been developed.

In [10], a branch and boundary algorithm was used to select the ideal location for a substation. The method was encouraging when applied to realistically sized problems. However, the model was static and did not allow for variation in the demand with time. Furthermore, it did not include any constraints on voltage limits. In [11], for the distribution substation, using integer and linear programming based on a mathematical model that identifies the expansion plan with the lowest cost, an approach has been used to optimize the voltage, load, reserve requirements, and cost of substation capacities. The construction of a substation is determined by voltage forecasts. For the mentioned method, there is a limitation that the voltage forecasts are based on the presumption, and according to this presumption, load densities are uniform within a substation service area. Generally, this is not the case. There is also another limitation of the model that the location of the equipment is not taken into consideration. In [12], an optimization algorithm of a heuristic combination is proposed for the determination of the optimum location and size for distribution substations and is based upon placing the substations for minimization of the energy losses on the feeders. Selecting the candidate substation locations is not required on the procedure proposed by the Authors. In [13], an algorithm of a minimal path is used for the determination of future expansion capacities and sites for the substations. However, coordinates or optimum capacity for the transformers cannot be calculated by this method. In [14], a method for the determination of the expansion of a distribution system based upon a radial network with an algorithm of a separate branch exchange was developed. The algorithm proved to be effective and was validated by numerical examples and could be extended to calculate accurate losses and so provide planning for improved expansion of distribution systems. The approach, however, was limited by the complex structure of the problem and the requirements for memory and computational time, and thus, it could only be applied to small-scale systems. In [15], based on voltage drop, cost, and transformer location, the use of a genetic algorithm to plan the expansion of the power system was examined. good results were achieved by the algorithm but the results were being slowly produced and time-varying demand was not considered by the method. In [16], conducted a study on the location, sizing, equipment cost, feeder cost and, power loss of high and medium voltage transformers using a pseudo-dynamic methodology and genetic algorithms. They declared that their proposed method is very fast in comparison with direct search with sufficient accuracy. But it was not intended to find the transformer coordinates exactly. In [17], based on nonlinear optimization, an algorithm of a network flow was used for the determination of the transformer substations' location, energy loss, cost, security, and maintenance. The study concludes that systematic optimization can be valuable in the decision-making process, while sensitivity analysis can indicate the effects of assumptions for the input. In [18, 19], depending on load density and power for different voltage levels, geometric and mathematical equations were used for the determination of the CA of transformers. Network optimization studies have been carried out to estimate a total load of a city and loads of the existing substations to determine equal CA based on transformer power in the selection of substations. In [20], specific equations and methods are given for optimizing the power, location and load density of existing Low Voltage (LV) transformers. In this study, first of all, transformers that are actively operating in the existing network and whose coverage area overlapped were determined and tried to find the optimal power, load density and ideal location. With the findings obtained, it was ensured that the current network was removed from the intricate structure and brought to a state where there would be minimum overlap in the coverage areas by determining and applying the load sharing between the transformers.

Transformer capacity, the minimal cost of the High Voltage (HV) line among HV transformers, voltage drop, overall cost, and transformer CAs with fixed capacity are generally taken into account by existing studies to develop new plans for a network. Analysis of some studies base on existing equations and algorithms. Intending to optimize the network and increase efficiency, the presented study differs from existing ones by the adaptation of a CA-based approach for the determination of the distribution of new HV/LV transformers in an existing urban distribution network. While a study was made on the arrangement of the existing LV network in Reference 20, in this one, a study was made for the transformers to be deployed. These two works complement each other. The CAs are defined depending on the load density of the transformers in the network with this approach. Unique algorithms and equations are developed by the study to perform network optimization. In this way, where customer demand is not being met within an existing coverage area, the location, power, CA of a new transformer, and the route of the HV conductor determined so that it is not within the CA of the existing transformers.

In this study applies for distribution network planning to the Kupluce-Kirazlitepe (KK) region of the Vaniköy Electricity Distribution Operator of Uskudar district of Istanbul to examine the operation in its regions. The CA of the existing transformers was defined and a new approach applied to determine the power, location, and CA for the new transformer planned to be deployed. Besides, an approach was considered to plan a distribution network with a different method for the analyses of minimal HV distribution costs and routes.

2. Material and method

The CA of each substation depends on the transformer load factor, load density, the number, and the capacity of the transformers in the substation.

2.1. Load density (σ)

Load density is a measure of the total energy consumed per unit area. As load density varies, the value of the unit area may need to be varied to represent the specific and homogeneous distribution within an area. It can be a challenge to provide electrical power to these areas and predict their future load [19, 20].

2.2. Load factor (β)

The load factor is defined as the ratio of the total amount of electrical energy used within a specified period (average consumed load) to the instantaneous maximum consumption in the same period (Eq. (1). In general, the load factor ranges from 0.5 to 0.7 and can be considered as an average of 0.6 per year [18–21].

$$\beta_i = \frac{S_{ave}}{S_{max}} \tag{1}$$

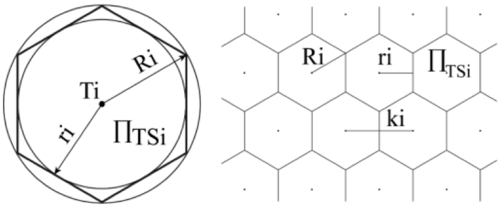

Fig. 1. Transformer CA template model.

Here;

S_{ave} *Average consumed load* (VA)

S_{max} *Highest consumed load* (VA)

2.3. *Structure of the distribution network under investigation*

The distribution operator in the Uskudar District, Vaniköy region of Istanbul distributes HV to the 0.4 kV LV network at 34.5 kV and 10.5 kV. The total number of LV transformers is 250. Study examines the 10.5 kV voltage level distribution network and 94 piece LV transformer. This region includes two 60 MVA (T_{01} and T_{02}) 154/10.5 kV transformers that supply to 10.5/0.4 kV distribution transformers with ratings between 400 and 1600 kVA. The distribution network is determined by the feeders (n_i) from each 60 MVA transformer and the number of transformers connected to these feeders. Comprises 40 pieces 10.5/0.4 kV transformers fed from 8 feeders connected to the T_{01} transformer. Comprises 54 pieces 10.5/0.4 kV transformers fed from 11 feeders connected to the T_{02} transformer. There are in total 94 sub-feeders connected to the 19 feeders of these transformers. The Single Line diagram related to the specified distribution network is given in the Appendix. In this study, our new methods are applied to the Kupluce-Kirazlitepe (KK) region.

2.4. *Finding CA and internal, external radii depending on transformer power and load density*

Generally, the CA of substations can be perceived to be arbitrary and intricate, depending on the location and rating of the transformers. However, with geometric and mathematical modelling of the transformers in the distribution network, the coverage and radius are determined based on the best possible capacity for the substations. The modelling is based on the principle of hexagonal geometric patterns, together with the mathematical relationships between network parameters, as the ideal surface coverage method. Fig. 1 shows this applied to all hierarchical levels of transformers. modelled from Fig. 1Eqs. (2), (3), (4), and (5) are used to determine the coverage areas of transformers.

$$\sigma_i = \frac{S_{ri} - S_{ri}^{'}}{R_i^2} \tag{2}$$

$$\Pi_{TS\ i} = 2.6 \cdot R_i^2 = \frac{n_i \cdot \beta_i \cdot S_{ri}}{\sigma_i \cdot 1000} \tag{3}$$

$$R_i = 0.62 \cdot \sqrt{\Pi_{TS\ i}} = 0.62 \cdot \sqrt{\frac{n_i \cdot \beta_i \cdot S_{ri}}{\sigma_i \cdot 1000}} \tag{4}$$

$$r_i = 0.54 \cdot \sqrt{\Pi_{TS\ i}} = 0.54 \cdot \sqrt{\frac{n_i \cdot \beta_i \cdot S_{ri}}{\sigma_i \cdot 1000}} \tag{5}$$

Here;

$\Pi_{TS\ i}$ CA (km^2)
σ_i load density of i th transformer (kVA/km^2)
$S_{r,\ i}$ rated capacity of i- th transformer (kVA)
$S_{r,\ i}^{'}$ empty capacity of i th transformer (kVA)
R_i coverage of i th outer circle tangent radius (km)
r_i coverage of i th inner circle tangent radius (km)
n_i number of transformers in the i th station
T_i transformer code
β_i load factor of i th transformer
k_i Distance between two transformers (km) [20, 21].

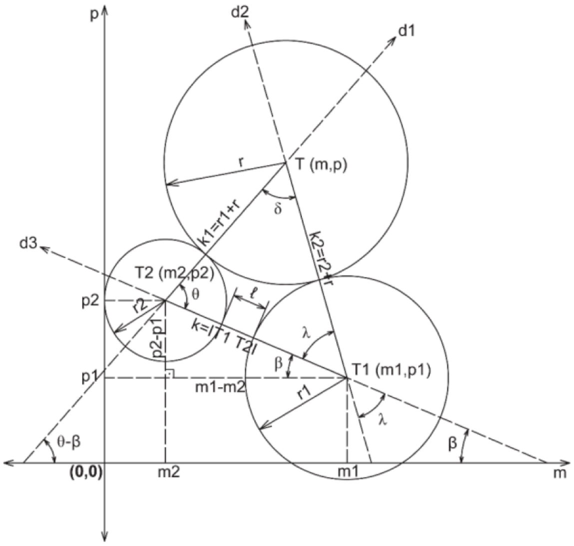

Fig. 2. Finding location and CA of a third transformer from locations and CA of two existing transformers.

Data from the year 2018 were used transformer power, load density, the Cartesian coordinates of each transformer, and the number of transformers in each feeder. The load factor (β_i) of the network was taken as 0.6. The load density (σ_i), CA (Π_{TSi}), outer (R_i) and inner (r_i) radius of each transformer was calculated using Eqs. (2), (3), (4) and (5).

2.5. *Finding the coverage areas, position, and power ratings of new distribution transformers*

The Transformers, which are the most important parameter in distribution network planning, must be determined for both position and power rating. Two general cases need to be examined:

- Third transformer added to extend network coverage outward (extra-grid); location, coverage and power rating determined from the location and CA of two existing transformers in the electricity distribution network.
- Fourth transformer added within existing coverage to improve supply (inter-grid); location and power rating determined from the location, power rating and CA of three existing transformers in the electricity distribution network.

This study considers both cases and applies our methods and techniques to examples in the KK region [21].

2.6. *Extending coverage by finding the location and CA of the third transformer from the location and CA of two existing transformers*

The location and CA of a new transformer to extend coverage, and the route of the HV conductor, will be determined to provide for customer demand, with the most likely location being close to the customer. The method for extra-grid expansion considers the load density, the power rating of existing transformers, the number of transformers in the feeder to which it is connected, grid load factor, and

Cartesian coordinates, to determine the new location. In this context, original variables and equations were created based on the analytical and geometric figure developed by us, which can be seen in Fig. 2. The method to find the position and CA of a third transformer from two existing transformers is shown in Fig. 2.

The distance between the two existing transformers may be found from the general formula (6):

$$|T_1\ T_2| = k = \sqrt{(m_1 - m_2)^2 + (p_1 - p_2)^2} \tag{6}$$

m_i Longitude: x, p_i Latitude: y,

From which other distances to the new transformer may be found (7):

$$l = k - (r_1 + r_2),\ \ k_1 = r_1 + r,\ \ k_2 = r_2 + r \tag{7}$$

l The distance of the line between the centre points of the two transformers outside CA

The angle β in Fig. 2 can be found from the length of the edges of the perpendicular triangle formed by the transformer centres T_1 and T_2 as (8),

$$\beta = \left[\left|\frac{(m_2 - m_1)}{k}\right|\right] \tag{8}$$

When the location of the transformer substations T_1, T_2 and T have been determined, the area of the triangle with internal angles θ, λ, δ and known edge lengths may be calculated from Eq. (9) and (10).

$$\varepsilon = \left[\frac{(k + k_1 + k_2)}{2}\right] \tag{9}$$

$$\Delta_\varepsilon = \sqrt{\varepsilon\cdot(\varepsilon - k_1)\cdot(\varepsilon - k_2)\cdot(\varepsilon - k)} \tag{10}$$

Where:

ε_i The edge length is half the sum of the perimeter of the known triangle,

Δε Area of triangle with known edge length,

Given the area of the triangle with known edges may be calculated from (11):

$$\Delta_\varepsilon = \frac{1}{2}\cdot k_1\cdot k\cdot sin\, sin\, \lambda \tag{11}$$

We can find the angle λ from (10) and (11) as (12):

$$\lambda = \left[\frac{2\cdot\sqrt{\varepsilon\cdot(\varepsilon - k_1)\cdot(\varepsilon - k_2)\cdot(\varepsilon - k)}}{k\cdot k_1}\right] \tag{12}$$

And

$$\phi = \beta + \lambda \tag{13}$$

If: $m_1 < m_2$, $p_1 < p_2$ and $p > p_1$ then we have:

$$m = m_1 + k_1\cdot cos\, cos\, \phi \tag{14}$$

$$p = p_1 + k_1\cdot sin\, sin\, \phi \tag{15}$$

else if: $m_1 > m_2$, $p_1 < p_2$ and $p > p_1$ then:

$$m = m_1 - k_1\cdot cos\, cos\, \phi \tag{16}$$

$$p = p_1 + k_1\cdot sin\, sin\, \phi \tag{17}$$

else if: $m_1 > m_2$, $p_1 > p_2$ and $p < p_1$ then:

$$m = m_1 - k_1\cdot cos\, cos\, \phi \tag{18}$$

$$p = p_1 - k_1\cdot sin\, sin\, \phi \tag{19}$$

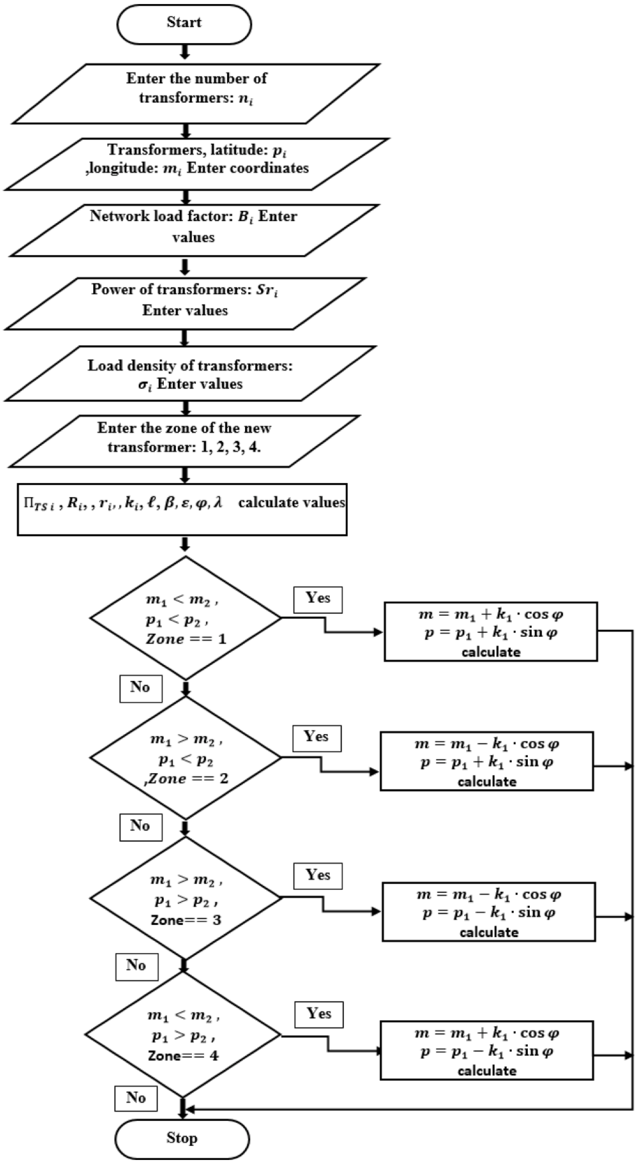

Fig. 3. Algorithm to find location and CA of third transformer.

else if: $m_1 < m_2$, $p_1 > p_2$ and $p < p_1$ then:

$$m = m_1 + k_1\cdot cos\, cos\, \phi \tag{20}$$

$$p = p_1 - k_1\cdot sin\, sin\, \phi \tag{21}$$

Equations (6)(21) are applied as in the algorithm of Fig. 3, together with the power flow density of the two transformers, the location and the number of feeders to which they are connected, to determine the location and CA of the third transformer.

2.7. Finding the location, power rating, and CA of a fourth transformer from the location and CA of three existing transformers

Where customer demand is not being met within an existing coverage area, the location and CA of a new transformer and the route of the HV conductor should be determined so that it is not within the CA of the existing transformers. The intra-grid expansion method considers the power ratings of the existing transformers, the number of transformers in the feeder to which it is connected, load density, grid load factor, and Cartesian coordinates. In this context, original variables and equations were created based on the analytical and geometric figure

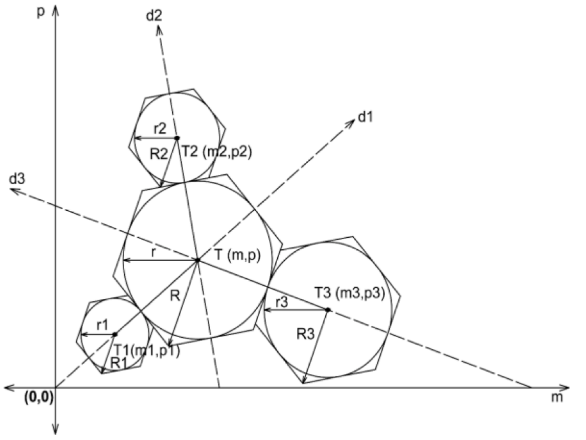

Fig. 4. Finding the location, power and CA of a fourth transformer from location and CA of three existing transformers.

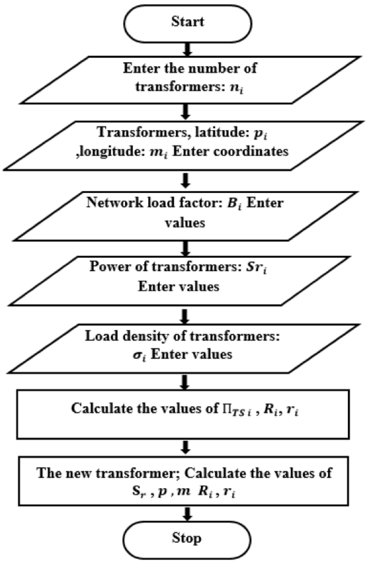

Fig. 5. Flow chart to determine location, CA and power algorithm of fourth transformer.

developed by us, which can be seen in Fig. 4. Fig. 4 shows the method.

$$|T\,T_1\,| = k = \sqrt{(m-m_1)^2 + (p-p_1)^2} \tag{22}$$

$$|T\,T_1\,| = (r+r_1) \tag{23}$$

$$|T\,T_2| = k = \sqrt{(m-m_2)^2 + (p-p_2)^2} \tag{24}$$

$$|T\,T_2\,| = (r+r_2) \tag{25}$$

$$|T\,T_3| = k = \sqrt{(m-m_3)^2 + (p-p_3)^2} \tag{26}$$

$$|T\,T_3\,| = (r+r_3) \tag{27}$$

The distance between the transformers may be found from Eqs. (22) to (27). By equating Eqs. (23), (25) and (27) for r, we obtain Eqs. (28) and (29):

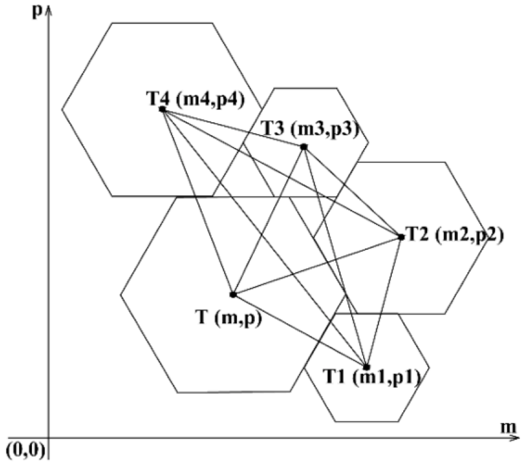

Fig. 6. Finding the optimal conductor route of the HV transmission line.

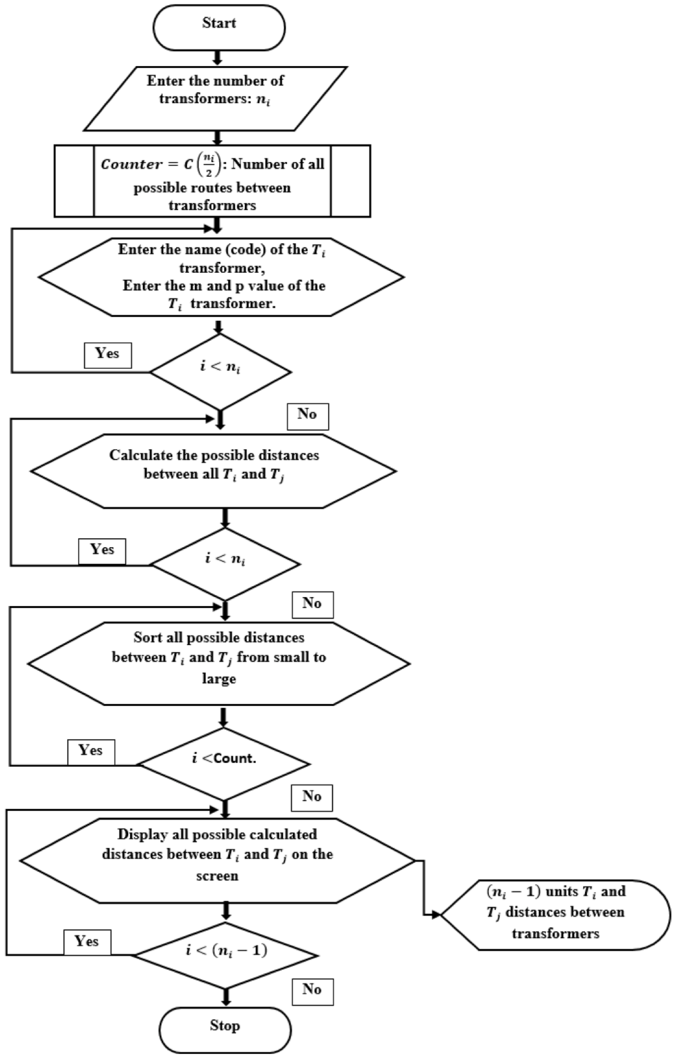

Fig. 7. Flow chart of the algorithm to determine the optimal wiring route between transformers.

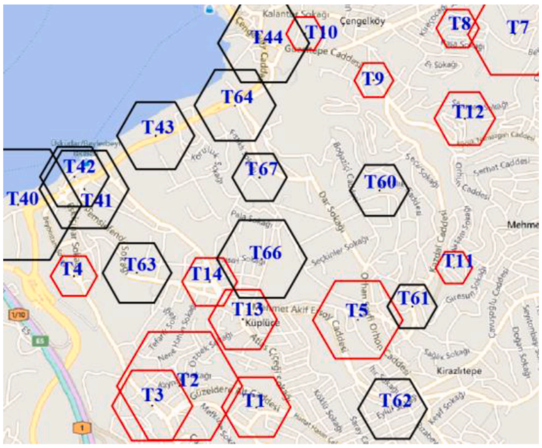

Fig. 8. Coverage areas of 10.5 kV LV substations in KK region.

$$\sqrt{(m-m_1)^2+(p-p_1)^2}-\sqrt{(m-m_2)^2+(p-p_2)^2}=r_1-r_2 \tag{28}$$

$$\sqrt{(m-m_1)^2+(p-p_1)^2}-\sqrt{(m-m_3)^2+(p-p_3)^2}=r_1-r_3 \tag{29}$$

If we equate (28) and (29) through r$_1$, we can calculate the coordinates p and m at which the new transformer should be located:

$$\begin{aligned}&\sqrt{(m-m_1)^2+(p-p_1)^2}-\sqrt{(m-m_2)^2+(p-p_2)^2}+r_2\\&=\sqrt{(m-m_1)^2+(p-p_1)^2}-\sqrt{(m-m_3)^2+(p-p_3)^2}+r_3\end{aligned} \tag{30}$$

$$r\;=\;\sqrt{(m-m_1)^2+(p-p_1)^2}\;-r_1 \tag{31}$$

Eq. (31) may then be used to calculate the internal radius r of the CA of the new transformer. The algorithm to calculate the location of the new transformer from these equations is shown in Fig. 5.

The power density of the three transformers, the number of feeders to which they are connected, and coverage and power rating of the fourth transformer may then be found.

2.8. *Determination of optimal route for hv line between transformers*

The approach to finding the optimal length and route of the HV transmission line which will feed a transformer is obtained by considering Fig. 6, from which Eqs. (33) and (34) are derived.

Eq. (32) gives the line length between two transformers, Eq. (33) gives the number of possible routes, and (n_i −1) gives the optimum wiring route number.

$$|T\,T_i\,|=k_i=\sqrt{(m-m_i)^2+(p-p_i)^2} \tag{32}$$

$$N=C\binom{n_i}{2} \tag{33}$$

Where,

N is number of possible routes, and $|T\,T_1\,|$, $|T\,T_2\,|$, $|T\,T_3\,|$, $|T\,T_4\,|$, $|T_1\,T_2\,|$, $|T_1\,T_3\,|$, $|T_1\,T_4\,|$, $|T_2\,T_3\,|$, $|T_2\,T_4\,|$ and $|T_3T_4\,|$ are possible variants of conductor route of the HV.

Using these equations, the shortest distance for the LV or HV route can be selected. Fig. 7 shows the flow chart to calculate the optimum cable route and length between transformers.

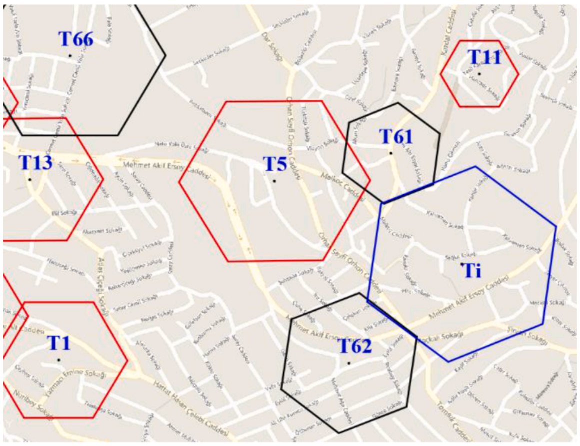

Fig. 9. CA of the newly deployed T$_i$ transformer in the KK region.

3. Evaluation

3.1. *Uskudar KK region electricity distribution network structure and transformer coverage area*

The Uskudar KK region consists of 25 LV distribution transformers of different power values as shown in Fig. 8. It is supplied from transformers T$_{01}$ and T$_{02}$, each with a voltage level of 154/10.5 kV and a rating of 60 MVA. As indicated in Fig. 8, in transformer T$_{01}$ of 60 MVA; T$_1$ and T$_5$ transformers connected to K$_5$ feeder are 1000 T$_8$-T$_9$-T$_{10}$ transformer is 630 kVA. T$_{11}$-T$_{12}$-T$_{14}$ transformers connected to K$_6$ feeder consist of 630 kVA transformer and T$_{13}$ transformer consist of 1600 kVA transformer.

In the T$_{02}$ transformer of 60 MVA; T$_{40}$ transformer connected to K$_{21}$ feeder is 630 kVA, T$_{43}$ transformer is 800 kVA, T$_{41}$ and T$_{42}$ transformers are 1000 kVA, T$_{44}$ transformer is 1600 kVA. T$_{60}$ and T$_{61}$ transformers connected to feeder B$_1$ are 1000 kVA and T$_{62}$ transformer is 1600 kVA. T$_{63}$ and T$_{67}$ transformers connected to K$_{22}$ feeder consist of 630 kVA transformers, T$_{64}$ and T$_{66}$ transformers consist of 1000 kVA transformers.

3.2. *Finding the location and CA of the third transformer from the location and CA of the two transformers*

The T$_{61}$-T$_{62}$ transformers of the KK region are taken as an example of extra-grid expansion. In extra-grid expansion, a new distribution network needs to be established to supply the settlements that will be formed from the growth of a city or town area. If the transformers located in areas adjacent to the new region cannot meet the increased demand, then a new LV distribution network and HV transmission line is required. The location and CA of the new transformer will be determined to provide power to areas not able to be supplied by existing transformers.

Take for example a new zone that is proposed for development between Mehmet Akif Ersoy Street and Saglik Street. If the increased power cannot be supplied from the nearest transformers (T$_{61}$ and T$_{62}$),

Table 1
Technical specifications of T$_{61}$ and T$_{62}$ transformers and calculated values of the new T$_i$ transformer.

No	Code	n$_i$	Sr, i (kVA)	σ$_i$ (kVA/ km^2)	m	p	R$_i$ (km)	r$_i$ (km)	Π $_{TS\ i}$ (km^2)
1	T$_{61}$	3	1000	55.92	421,135	4,545,334	0.1112	0.0969	0.0322
2	T$_{62}$	3	1600	46.76	421,046	4,544,877	0.1539	0.1340	0.0616
New	**T$_i$**	**4**	**1000**	**20**	**421,284**	**4,545,093**	**0.2148**	**0.1817**	**0.120**

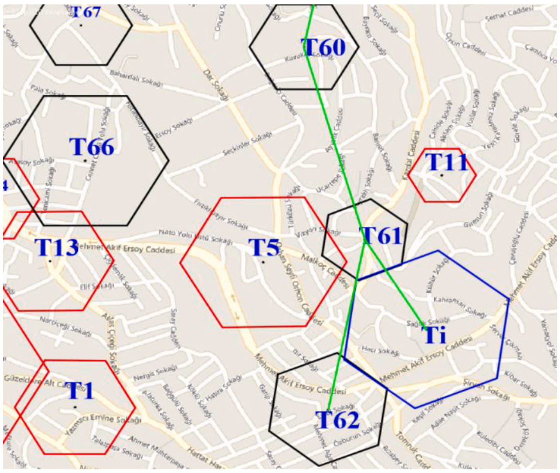

Fig. 10. The shortest HV line route to T_i transformer.

or the distance of the new development is too far from the existing transformers resulting in too great a loss, then a new transformer will be required. The location of this new transformer must be in such a location that it does not impinge on the CA of the closest existing transformers. The specifications for the existing transformers, T_{61}-T_{62}, are given in Table 1.

3.3. Calculation of the power, location, and ca of the third transformer

The data of the existing T_{61} and T_{62} transformers are used in the algorithm of Fig. 3 to determine the location, CA and power of the T_i transformer. The calculated value of the new T_i transformer are given in Table 1, and of the location and CA is indicated in Fig. 9.

3.4. Finding the HV line for the transformer to be deployed using two transformers

When the T_i transformer is deployed, a new HV line will be required to connect it to the distribution network. Normally this will connect to the nearest transformer, but will also depend on the number and load of the feeders. As shown in Fig. 10, the T_{60}-T_{61}-T_{62} transformers are fed from the B_1 feeder. The algorithm of Fig. 7 may be used to determine the optimum route for the HV line to the new T_i transformer. The calculations for this new HV line are given in Table 2.

As can be seen from Table 2, the shortest distance between T_{61} and T_i is 284 m, between T_{62} and T_i is 321 m, and between T_{60} and T_{61} is 539 m. The transformers in all feeders have been added in a linear fashion that simplifies calculation of line loads and lengths. Here, T_{60} to T_{61} is 539 m and T_{61} to T_{62} is 466 m. If T_i were to be added in the same linear fashion, then it would be connected to T_{62}, with the route between T_{62} and T_i being 321 m. However, our algorithm has determined that the distance between T_{61} and T_i at 284 m is the shortest distance to an existing transformer. This connection is shown in Fig. 10 and how a minimum the optimum route is created.

3.5. Finding the location, power, and CA of the fourth transformer from the position and CA of three transformers

It is assumed that there will be a new development between Saray Street and Atlas Flower Street in the KK region. If the required power cannot be met from the nearest transformers, T_1-T_5-T_{13}, then a new transformer will be required. The power and location of this transformer should be in an optimal location so that it does not impinge on the coverage areas of the existing transformers. The specifications of T_1-T_5-T_{13} transformers are given in Table 3.

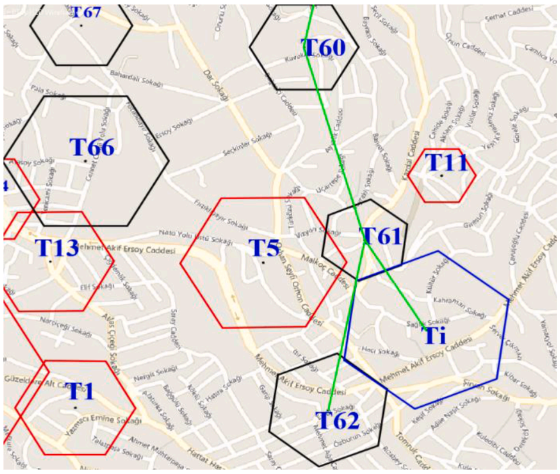

Fig. 11. CA of the newly deployed T_i transformer in the KK region.

Table 2
Determination of optimal HV line route to KK T_i transformer.

No	Code	Sr, i (kVA)	m	p	Algorithm Calculation Result	
1	T_{60}	1000	420,988	4,545,853	Distance from T_{60} to T_{61} = 539 m	HV Transmission Route
2	T_{61}	1600	421,135	4,545,334	Distance from T_{60} to T_{62} = 979 m	T_{61} to T_i = 284 m
3	T_{62}	1600	421,046	4,544,877	Distance from T_{60} to T_i = 816 m	T_{62} to T_i = 321 m
New	T_i	1000	421,284	4,545,093	Distance from T_{61} to T_{62} = 466 m	T_{60} to T_{61} = 539 m
$N = C\left(\frac{n_i}{2}\right)$: *Length of all possible routes between transformers*					Distance from T_{61} to T_i = 284 m	(n_i −1) units T_i and T_j distances between transformers
(*Binary combination of transformer numbers*)					Distance from T_{62} to T_i = 321 m	

Table 3
Technical specifications of T_1-T_5-T_{13} transformers and calculated values of the new T_i transformer.

No	Code	n_i	Sr, i (kVA)	σ_i (kVA/ km^2)	m	p	R_i (km)	r_i (km)	$\Pi_{TS\ i}$ (km^2)
1	T_1	7	1000	76.38	420,435	4,544,883	0.1454	0.1266	0.0550
2	T_5	7	1000	40.02	420,890	4,545,274	0.2009	0.1749	0.1049
3	T_{13}	4	1600	62.16	420,375	4,545,277	0.1541	0.1342	0.0617
New$_1$	**T_i**	**5**	**823**	**30.00**	**420,607**	**4,545,106**	**0.1749**	**0.1541**	**0.0823**
New$_2$	**T_i**	**5**	**1000**	**24.69**	**420,607**	**4,545,106**	**0.1749**	**0.1541**	**0.0823**

*The algorithm calculates 823 kVA New$_1$, but since there is no 823 kVA transformer, 1000 kVA New$_2$ transformer is selected.

Table 4
Determination of optimal HV line route to KK T_i transformer.

No	Code	Sr, i (kVA)	m	p	Algorithm Calculation Result	
1	T_{11}	630	421,321	4,545,508	Distance from T_{11} to $T_{12} = 669$ m	HV Transmission Route
2	T_{12}	630	421,370	4,546,175	Distance from T_{11} to $T_{13} = 974$ m	T_{13} to $T_{14} = 225$ m
3	T_{13}	1600	420,375	4,545,277	Distance from T_{11} to $T_{14} = 1097$ m	T_{13} to $T_i = 288$ m
4	T_{14}	630	420,226	4,545,445	Distance from T_{11} to $T_i = 819$ m	T_{12} to $T_{13} = 1340$ m
New$_2$	T_i	1000	420,607	4,545,106	Distance from T_{12} to $T_{13} = 1340$ m	T_{11} to $T_{12} = 669$ m
$N = C\left(\frac{n_i}{2}\right)$: *Length of all possible routes between transformers*					Distance from T_{12} to $T_{14} = 1357$ m	($n_i - 1$) units T_i and T_j distances between transformers
(*Binary combination of transformer numbers*)					Distance from T_{12} to $T_i = 1314$ m	
					Distance from T_{13} to $T_{14} = 225$ m	
					Distance from T_{13} to $T_i = 288$ m	
					Distance from T_{14} to $T_i = 510$ m	

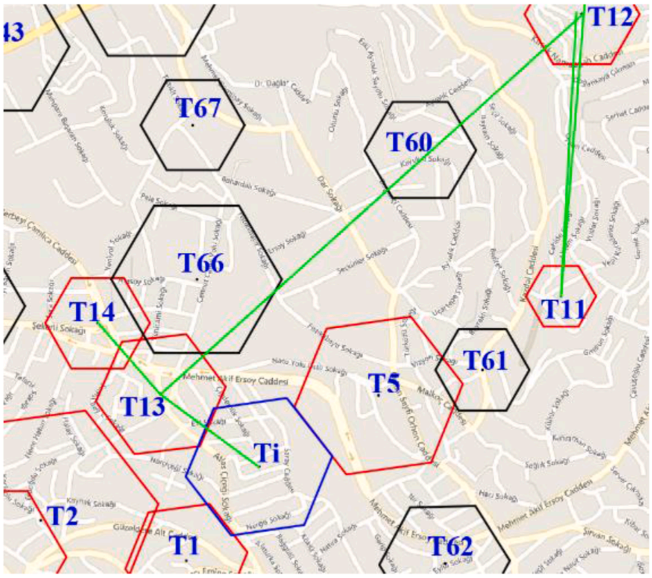

Fig. 12. The shortest HV line route to the KK T_i transformer.

3.6. Calculation of the power, position, and CA of the fourth transformer

All The data of the existing T_1, T_5 and T_{13} transformers are used in the algorithm of Fig. 5 to determine the location, CA and power of the T_i transformer. The calculated value of the new T_i transformer are given in Table 3, and of the location and CA is indicated in Fig. 11.

3.7. Finding the HV line for the transformer to be deployed using three transformers

A new HV line will be required to connect the T_i transformer to the distribution network. This should be to the nearest transformer, but may also depend on the number and load of the feeders. In this case, transformers T_0-T_1-T_2-T_3-T_4-T_5-T_6 are fed from feeder K_5, and transformers T_{11}-T_{12}-T_{13}-T_{14} are fed from feeder K_6. The K_5 feeder has seven transformers and an existing total load of 4590 kVA, K_6 feeder has four transformers and an existing total load of 3490 kVA. The new T_i transformer has a projected load of 10,000 kVA. In this case, due to loading, it would be preferred to connect the new HV line to feeder K_6. The algorithm of Fig. 7 is then applied to determine the optimum route for the HV line. The determination and result is given in Table 4.

Table 4 indicates the shortest distance between T_{11} and T_{12} is 669 m, T_{12} and T_{13} is 1340 m, T_{13} and T_{14} is 224 m, and T_{13} and T_i is 288 m; these connections would represent the minimum length for full connection of all transformers. Before the addition of the T_i transformer, the HV path is sequential; T_{11} to T_{12} is 669 m, T_{12} to T_{13} is 1340 m and T_{13} to T_{14} is 224 m. These routes are shown in Fig. 12.

Here, T_{11} to T_{12} (669 m), T_{12} to T_{13} (1340 m), and T_{13} to T_{14} (224 m) are connected in a strict linear sequence. Therefore, according to this approach, the route between T_{14} and T_i (510 m) would be selected for the new transformer. However, according to our algorithm, the distance between T_{13} and T_i (288 m) is shorter and to be preferred. In addition, as seen in Fig. 12, it would be preferred to follow a direct route from T_{11} to T_{13} (973 m) in place of the current HV route from T_{12} to T_{13} (1340 m), giving a reduction in total cable length of 367 m, with consequent reduction in conductor cost and voltage drop.

3.8. Voltage drop losses and cost analysis

As the location of any new transformer will have a direct impact on the cost of installation and energy loss, we analyse the separate solutions for the two cases that effect on cost. According to current conditions HV underground 3×95 mm^2 NYY copper insulated cable's canal opening in underground, cable laying, under and over cable filling, plate coating, sign strip and license fee is 1 m the cost approximately $K_m = 500$ TL [22]. In the first case, the wiring cost, K_m, between T_{62} and T_i would be 160 500 TL. This compares with the wiring cost, K_m, between T_{61} and T_i, which would be 142 500 TL. In the second case, the wiring cost, K_m, between T_{14} and T_i would be 255 000 TL, whereas the wiring cost, K_m, between T_{13} and T_i would be 144 000 TL. In both cases, there is a significant saving. In addition, if our proposed change to use the route T_{11} to T_{13} were adopted, then the cost would be 486 792 TL, in place of the current cost for the route T_{12} to T_{13} of 670 185 TL. The voltage drop in any three-phase network is considered as energy loss and loss of revenue; the voltage drop will be dependent on the cable length. However, when we calculated the cost due to lost energy, this was found to be insignificant in all cases compared to the reduction in cable cost and is neglected.

4. Conclusion

In this study, we describe an algorithm to determine the optimal location and power for a newly deployed transformer to manage the changing demand for supply. In the case of in-grid expansion, we determine the CA of the new transformer to avoid overlap of coverage with existing transformers. In the case of extra-grid expansion, we determine an optimum position in relation to existing transformers to provide coverage to the new area.

We then describe our algorithm to determine the optimum route for the HV distribution network between the transformers to minimize distance and thus cost and voltage drop. In this way, under the heading of economy, which is a parameter of distribution network planning; It is ensured that each transformer is loaded in such a way that the coverage areas do not overlap and by this way energy losses are reduced. In addition, transformer power and size, transformer cabin area, feeder size, cable cross-section, protection equipment, assembly, labor and time-related costs are brought to the optimal level. Network planning using proposed algorithms on a smart network that provides measurement data will result in more efficient, cost-effective, and reliable networks.

CRediT authorship contribution statement

Onur Akar: Conceptualization, Methodology, Software, Validation, Writing – original draft. **Umit Kemalettin Terzi:** Validation, Data curation, Writing – review & editing. **Okan Ozgonenel:** Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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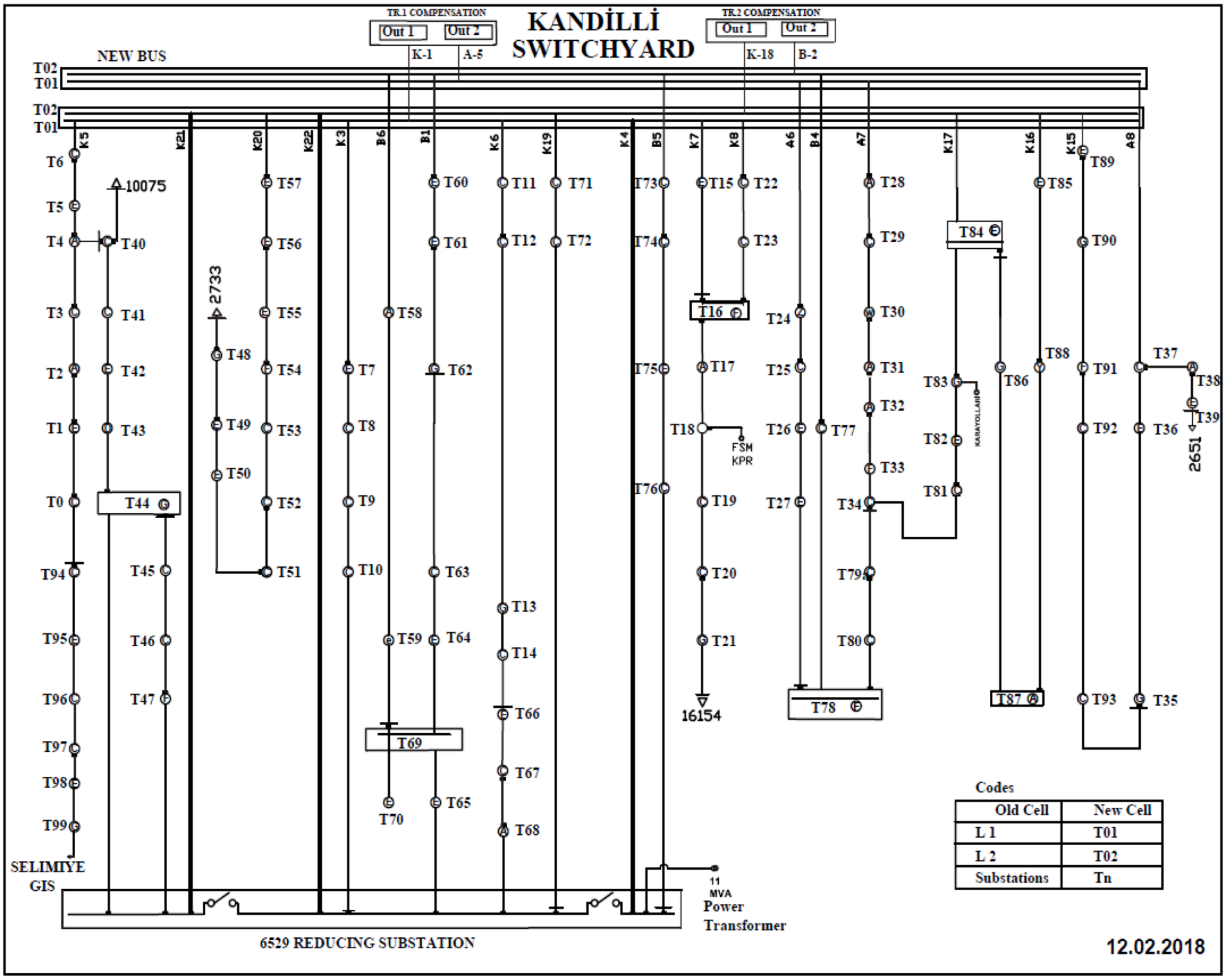
Appendix

Single line diagram of the distribution grid is given in below. Fig. 13



Codes

Old Cell	New Cell
L 1	T01
L 2	T02
Substations	Tn

Fig. 13. The shortest HV line route to the KK T_i transformer.

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